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Rotating machine fault diagnosis through enhanced stochastic resonance by full-wave signal construction

Siliang Lu [a,b], Qingbo He [c,*], Haibin Zhang [c], Fanrang Kong [c]

[a] College of Electrical Engineering and Automation, Anhui University, Hefei, Anhui 230601, PR China
[b] National Engineering Laboratory of Energy-Saving Motor & Control Technology, Anhui University, Hefei, Anhui 230601, PR China
[c] Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei, Anhui 230026, PR China

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ABSTRACT

This study proposes a full-wave signal construction (FSC) strategy for enhancing rotating machine fault diagnosis by exploiting stochastic resonance (SR). The FSC strategy is utilized to transform a half-wave signal (e.g., an envelope signal) into a full-wave one by conducting a Mirror–Cycle–Add (MCA) operation. The constructed full-wave signal evenly modulates the bistable potential and makes the potential tilt back and forth smoothly. This effect provides the equivalent transition probabilities of particle bounce between the two potential wells. A stable SR output signal with better periodicity, which is beneficial to periodic signal detection, can be obtained. In addition, the MCA operation can improve the input signal-to-noise ratio by enhancing the periodic component while attenuating the noise components. These two advantages make the proposed FSCSR method surpass the traditional SR method in fault signal processing. Performance evaluation is conducted by numerical analysis and experimental verification. The proposed MCA-based FSC strategy has the potential to be a universal signal pre-processing technique. Moreover, the proposed FSCSR method can be used in rotating machine fault diagnosis and other areas related to weak signal detection.

1. Introduction

A rotating machine, e.g., bearing, gear, and rotor, plays a critical role in industrial equipment. Rotating machines always endure heavy loads under operating condition, and thus structural faults, such as wear, pitting, or breakage, may occur after a long period of running [1]. A slight fault may cause a machine stop, but a severe fault can lead to a catastrophe. Therefore, fault diagnosis and condition-based maintenance for rotating machines are important in both reducing breakdown loss and guaranteeing personal safety [2,3]. When fault occurs in a rotating machine, some fault-induced signatures, e.g., periodical impulses, emerge in the acquired vibration or acoustic signals [4]. Fault types and fault severities can be estimated by analyzing the impulse period and the impulse intensity. However, the acquired signals always contain undesired noise that come from coupled component vibration in equipment and (or) work environment. Thus, signal pre-processing techniques such as noise filtering should be conducted to eliminate or attenuate the noise interference and to improve the signal-to-noise ratio (SNR) [5]. For instance, the removal of discrete frequency noise using self-adaptive noise cancellation for

* Corresponding author.
E-mail address: qbhe@ustc.edu.cn (Q. He).

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analyzing vibration signals was introduced in Ref. [6]. An adaptive filtering was performed for the background noise removal of vibration signals emanating from gearboxes based on Morlet wavelet analysis and conventional optimization methods [7]. A method for noise and outlier removal from jet engine health signals using weighted finite impulse response (FIR) median hybrid filters was proposed in Ref. [8]. These traditional linear or nonlinear filters that are manipulated in frequency domains focus on noise suppression. However, noise suppression may simultaneously attenuate target signal intensity if the target signal frequency is involved in the noise bandwidth.

Aside from noise suppression-based filters, such as the FIR filter, infinite impulse response filter, or wavelet filter, another kind of nonlinear filter called stochastic resonance (SR) filter can utilize noise energy to enhance the useful signal [9–11]. In the last decade, SR filters have been widely adopted in rotating machine fault diagnosis to enhance weak periodic signal by exploiting the noise [10,12–23]. For instance, a weak signal detection strategy for rotating machine fault diagnosis with multiscale noise tuning SR was introduced in Ref. [12]. An adaptive SR method for planetary gearbox fault diagnosis was proposed in Ref. [13]. A dual-scale cascaded adaptive SR method for rotary machine health monitoring was suggested in Ref. [14]. A study on a multi-frequency weak signal detection method based on SR tuning by multi-scale noise was performed in Ref. [15]. These efforts have effectively promoted SR research in rotating machine fault diagnosis.

The SR effect is influenced by two factors, namely, potential and input signals [22]. The distinct structure of the input signal (e.g., noise distribution, signal intensity, and signal integrity) significantly affects SR efficiency and output SNR. Currently, most of the fault diagnosis algorithms through the SR principle are based on classical SR theory, which can be briefly described as a periodic signal that can be enhanced by proper noise in a bistable potential. The periodic signal is always perceived as a full-wave signal with bipolarity, such as a zero-mean sinusoid or a zero-mean rectangular wave. However, in fault diagnosis, machine vibrations are modulated by fault-induced impulses. Thus, the modulated signal is usually demodulated by some envelope extraction approaches to better reveal the signal periodicity and make the signal capable of being addressed through the SR methods [12]. However, the envelope signal is a half-wave signal with unipolarity ($x(t) \geq 0$), and a unipolar signal cannot be processed directly using the SR methods because one of the bistable potential wells is located in the $x < 0$ region and the other in the $x > 0$ region. That is, the particle in the bistable potential can only oscillate in one well because the driving signal polarity is always positive. Particle oscillation between the two potential wells cannot be realized, and thus weak periodic signal detection through SR cannot be achieved. A traditional solution to overcome this inefficiency is the application of the zero mean normalization (ZMN) operation to the envelope signal to realize signal polarity transformation from unipolar to bipolar. However, the ZMN-based constructed signal is still a half-wave signal, and such a signal cannot evenly tilt the bistable potential back and forth. Thus, the potential cannot provide equivalent transition probabilities for particles to bounce between the two potential wells. Consequently, the periodicity of the SR output becomes irregular, and the weak signal detection performance is limited.

This study is committed to investigate the SR efficiencies under the half-wave signal and full-wave signal excitations and to improve the SR effect using a new Mirror–Cycle–Add (MCA)-based full-wave signal construction (FSC) strategy. The MCA operation involves three steps: 1) obtaining a Mirror signal of the original half-wave signal, 2) cyclic shifting the Mirror signal, and 3) adding the Mirror–Cycle signal to the original one and obtaining the constructed full-wave signal. The constructed signal evenly modulates the bistable potential and makes the potential tilt back and forth smoothly. It provides the approximately equivalent particle transition probabilities between the two potential wells and finally produces a better SR output. Moreover, the MCA operation can improve the input SNR by enhancing the periodic signal component while attenuating the noise level, which is also beneficial in obtaining a better output. The proposed MCA-based FSC strategy has the potential to be a universal signal pre-processing technique. Therefore, the proposed FSCSR method can be used in rotating machine fault diagnosis and other areas related to weak signal detection.

The rest of this paper is organized as follows: Section 2 investigates the SR efficiencies under half-wave signal and full-wave signal excitations, respectively, and then proposes a new MCA-based FSC strategy to enhance SR performance. Section 3 conducts a performance evaluation by analyzing different types of half-wave signals, noise levels, and signal duty cycles in comparison with the traditional ZMN-based SR method. Section 4 verifies the practicability of the proposed method by analyzing two sets of practical bearing defective signals and then provides the discussions. Section 5 summarizes this paper.

2. FSCSR

2.1. SR efficiencies under half-wave signal and full-wave signal excitations

The basis of the classical bistable SR phenomenon can be described as follows: a particle is driven by a periodic signal and random noise in a bistable potential consisting of two potential wells and one potential barrier, and the periodic oscillation can be enhanced with the assistance of proper noise. Such a phenomenon can be illustrated by the following governing equation under the assumption of overdamped situation:

$$\frac{dx}{dt} = -U'(x) + S(t) + N(t), \tag{1}$$

where $N(t) = \sqrt{2D}\,\xi(t)$, with $<N(t)N(t+\tau)> = 2D\delta(t)$ is the noise item, in which D is the noise intensity and $\xi(t)$ is an